Applications of Synthetic Aperture Radar to Meteorology and Oceanography Command Operations

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LONG-TERM GOALS

Our long-term goal is to employ near-surface wind speed derived from synthetic aperture radar (SAR) images of the sea surface as a marine meteorological research and forecasting tool. That is, we aim to use SAR-derived wind speed (SDWS) images to discover dynamical and morphological characteristics of microscale, mesoscale, and synoptic scale marine meteorological phenomena. We also aim to demonstrate how the fruits of our discovery can be used to aid marine meteorological analysts and forecasters.

OBJECTIVES

1. To develop software tools for portable, automated analysis of SDWS images with the objective of resolving intense mesoscale variability within those images.

2. To develop a SDWS-based system for automated verification of, and error-warning system for, mesoscale wind forecasts produced by numerical weather prediction (NWP) models. The emphasis will be on verification and error detection in those regions most challenging to mesoscale numerical weather prediction models—the near-shore zones adjacent to complex orography.

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14. ABSTRACT
Our long-term goal is to employ near-surface wind speed derived from synthetic aperture radar (SAR) images of the sea surface as a marine meteorological research and forecasting tool. That is, we aim to use SAR-derived wind speed (SDWS) images to discover dynamical and morphological characteristics of microscale, mesoscale, and synoptic scale marine meteorological phenomena. We also aim to demonstrate how the fruits of our discovery can be used to aid marine meteorological analysts and forecasters.

15. SUBJECT TERMS

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3. To empirically and theoretically investigate the phenomena responsible for the SDWS-signature of convectively-driven squall / lull couplets. The analysis will include the forcing, structure, and predictability of these intense mesoscale variations in the near-surface wind field. The goal is to incrementally step towards improved NWP model and statistical forecasts of this phenomenon.

In the context of these objectives, we have outlined five tasks:

Task 1. To develop a highly portable, efficient, and verifiable CMOD 4/5 hybrid software system for SDWS retrieval.

Task 2. To develop a fully automated system for mapping intense mesoscale variability in SDWS images.

Task 3. To determine the forcing, structure, and predictability of the convectively-driven open ocean squall / lull couplet features frequently seen within SDWS images.

Task 4. To develop a SDWS-based system for automated verification of, and error-warning system for, mesoscale wind forecasts produced by NWP models.

Task 5. To publish results in appropriate journals and present research at relevant conferences.

APPROACH

The basis of this research is the approximately 35,000+ SDWS image frames from the Bering Sea, Gulf of Alaska, East Coast of the United States, and the North Atlantic Ocean (from 1998 to present) contained in an archive at The Johns Hopkins University Applied Physics Laboratory (JHUAPL). This data is provided at no cost by Dr. Winstead. The image archive has been used extensively by the PIs to study atmospheric phenomena in the Gulf of Alaska. In addition to previous ONR-funded research of Drs. Sikora and Young (N00014-06-10046 [Sikora] and N00014-04-10539 [Young]), Drs. Winstead and Young participated in an NSF-sponsored study of barrier jets in the Gulf of Alaska using SDWS images. During the course of these research projects, a catalog of various imaged phenomena was generated by Drs. Sikora and Young (Stepp et al. 2007). This catalog documented a number of phenomena causing intense mesoscale variations in the near shore winds: gap flow exit jets (Figure 1), orographic gravity waves (Figure 2), and island wakes (Figure 3). In the open ocean, the most intense wind speed variability was caused by quasi-circular squall / lull couplets (Figure 4), described in Young et al. (2007). The arrows seen within each SDWS image are NWP model wind vectors. The approach described here is designed to automate the quantitative description of these intense mesoscale wind variations and lay the basis for forecasting them via a combination of numerical weather prediction and statistical post-processing.

The analytic foundation of the proposed SDWS analysis is software to produce SDWS based on CMOD4 (Stoffelen and Anderson 1997) and CMOD5 (Hersbach, 2007). Thus Task 1 was to use Dr. Winstead's expertise in CMOD and Dr. Young's expertise in software optimization, documentation, and testing to build a "technology transfer friendly" version of the existing JHUAPL CMOD system. The resulting Matlab software, including both CMOD4 and CMOD5, is available for public download from http://www.ems.psu.edu/~young/CMOD. The software is noteworthy in that it provides a fully documented testing and verification program, so that the user can both see how to implement calls to our CMOD functions and verify that the functions are working correctly on their system. To that end, the website also provides data files for system checkout and testing by users and a Word file

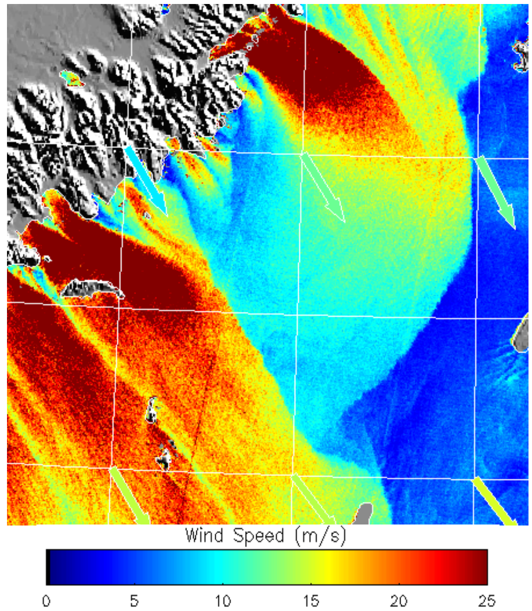

Figure 1. Radarsat-1 SDWS image depicting the signature of gap flow exit jets forced by stably-stratified flow through topography. The 600 m pixel image is 450 pixels by 450 pixels. The image was acquired off the coast of the Alaska Peninsula at 1635 UTC on 21 January 2006. (Provided courtesy of JHUAPL)

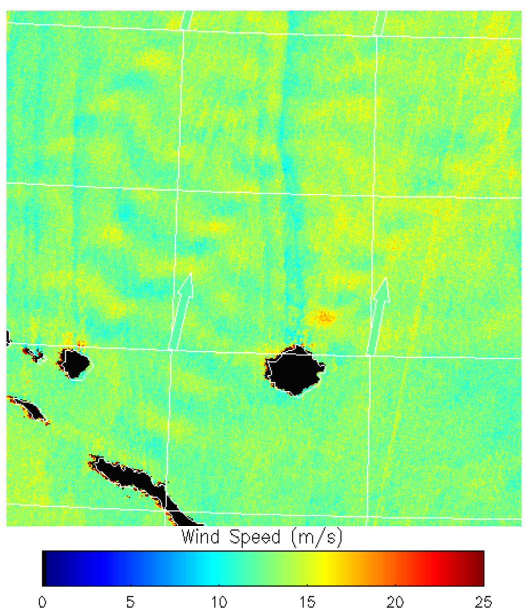

Figure 2. Radarsat-1 SDWS image depicting the signature of gravity waves forced by stably stratified flow over mountainous islands. The 600 m pixel image is 450 pixels by 450 pixels. The image was acquired off the Aleutians at 1808 UTC on 28 February 2006. (Provided courtesy of JHUAPL)

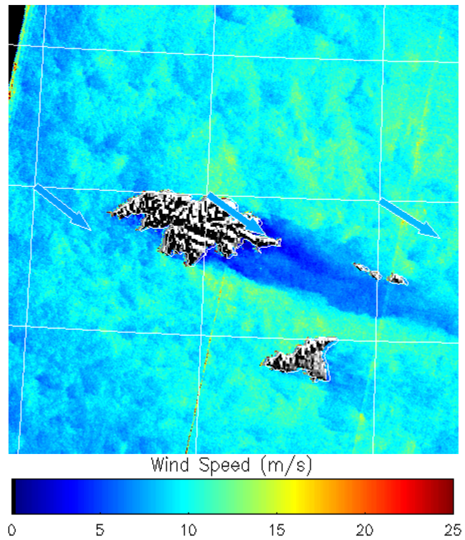

Figure 3. Radarsat-1 SDWS image depicting the signature of a slow wake forced by turbulent flow over a mountainous island. The 600 m pixel image is 450 pixels by 450 pixels. The image was acquired off Attu Island in the Aleutians at 1833 UTC on 30 March 2006. (Provided courtesy of JHUAPL)

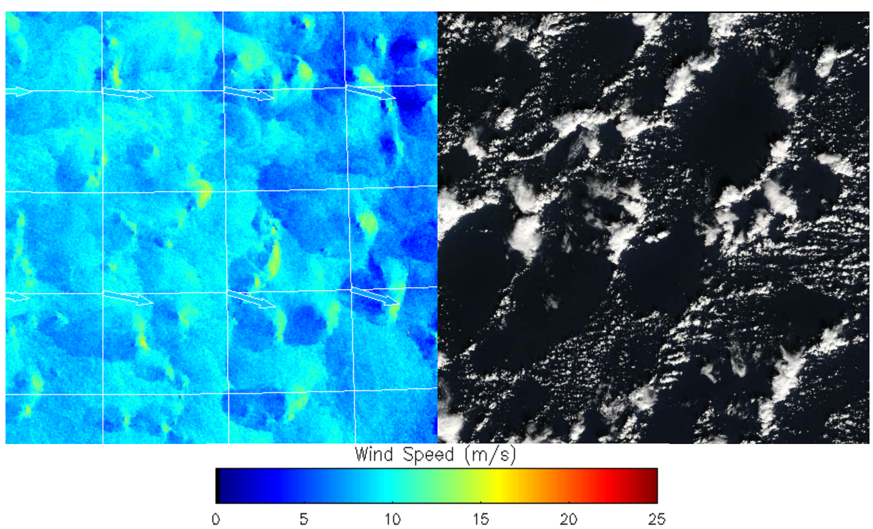

Figure 4. On the left is a Radarsat-1 SDWS image depicting the quasi-circular signatures of convectively-driven open ocean squall / lull couplets. The 600 m pixel image is 450 pixels by 450 pixels. The image was acquired over the Gulf of Alaska at 0301 UTC on 8 November 2006. The near-surface wind speed varies by a factor of two across the couplets (13 to 6.5 m/s). (Provided courtesy of JHUAPL) On the right is the closest corresponding MODIS image, a Terra satellite image of the region at 1955 UTC on 7 November 2006. The 250 m pixel image is 900 pixels by 900 pixels. It shows open-cell mesoscale cellular convection with a scale similar to the SDWS signatures. (Provided courtesy of NASA)

documenting the system and its use. The outcome of Task 1 is summarized in Fisher et al. (2007) and the documentation file on the website.

The other foundation of the proposed SDWS analysis is the ability to distinguish sharp-edged mesoscale variability of the wind speed field from the smooth background gradient imposed by synoptic scale weather systems. This task (Task 2) was approached as a digital filtering problem and objective analysis problem. Namely, feature extraction (via digital filtering) and pixel aggregation (via PCA and cluster analysis) techniques focused on mesoscale near-surface wind speed variability were tested. The meteorological features examined include gravity waves, convection cells, atmospheric fronts, island wakes, and gap flows. Twenty eight SDWS case study images possessing varying degrees of near-surface wind speed variability were selected from the JHUAPL archive for use in exploring the performance of these techniques and developing recommendations for future research. After applying a land mask (when necessary) to each image, the SDWS images were subjected to Gaussian high- and low-pass, and high pass local entropy, local standard deviation, local median, and Sobel edge detection filters. The filtered images were then assessed manually. The filtered output for each case was then used as input for the PCA and cluster analysis. Assessment was manual.

Convectively-driven squall / lull couplets at sea, the focus of Task 3, are not generally resolved by operational NWP models except when clusters of thunderstorms are involved. Yet such couplets are frequently observed in SDWS, even when no thunderstorms are present (Young et al. 2007). We examined open cell convection using two distinct but mutually supporting approaches. The first is a seven-year (1999-2006) climatology of the frequency of open cell convection and of its thermodynamic and kinematic environment, based on SDWS images and the NCAR/NCEP global reanalysis data. The second approach examines two-dozen case studies from the year 2006, which employ MODIS images, SDWS images, and MM5 maps, to document the morphology of open cell convection. Both approaches were used to reexamine the tropical squall line – open cell convection similarity and corresponding conceptual model of Young et al. (2007).

Between the years 1999 and 2006, 618 fields of open cell convection were observed in the SDWS image archive of the Gulf of Alaska following the methodology of Young et al. (2007). For each SDWS-detected event center location during the seven-year data collection, the nearest surface and upper air reanalysis from NCEP/NCAR global reanalysis archive was retrieved (sea surface temperature, air temperature at the surface, 925 hPa, 850 hPa, 700 hPa and 500 hPa, latent heat flux, sensible hear flux, as well as the u and v components of the wind). These data were used as part of the thermodynamic and kinematic climatology. The SDWS images were also used to identify the case studies for the cell morphology portion of this research. Those images with the best defined squall-lull signatures were chosen, with cases distributed as evenly as possible across seasons of the year. For each case, the latitude and longitude of a specific open cell on the SDWS image was documented, as well as the observed squall-lull orientation and maximum wind speed. For those same coordinates, the temperature, temperature advection, wind speed and direction, MCAPE, and the position relative to a cyclone were recorded from MM5 maps.

Warning of mesoscale wind speed variability in the near-shore region is both complicated by the numerous orographically generated mesoscale flows discussed above and aided by the partial resolution of these phenomena by mesoscale NWP models. Task 4 thus focuses on using SDWS to verify whether or not the NWP model forecasts valid at the SAR observation time are resolving the observed mesoscale wind speed variability, both near-shore and for the open ocean. Thus, SDWS will provide warning of ongoing events and information about how well the operational NWP model forecasts will capture future events of that type. The first stage in this analysis involves using model-derived wind directions to obtain a SDWS analysis from the backscatter image. The second stage involves filtering the SDWS image to highlight the mesoscale flow features and to quantify the extent to which those features are resolvable at a particular model's grid spacing. The third stage is a direct comparison between the SDWS analysis and the corresponding wind speed field forecast. If the two agree, then the model is not only resolving the flow but also the physics responsible for its creation. If a model passes both of these tests it can be expected to provide useful forecasts of mesoscale flows during similar synoptic situations in the future. In contrast, if the SAR and modeled wind speed fields disagree, either the model wind directions are wrong (causing SDWS errors) or the model is failing to adequately resolve the mesoscale wind speed field or its orographic forcing. In either case, the model is known to be doing a poor job of predicting the wind field.

WORK COMPLETED

Task 1:Technology transfer friendly software has been developed to infer near-surface wind speed from SAR backscatter based on CMOD4 and CMOD5. An evaluation of wind speed retrieval skill for CMOD4 and CMOD5 for a geographic region with intense mesoscale variability, the Gulf of Alaska, has been completed.

Task 2:A fully-automated filter-based system for mapping intense mesoscale variability in the near-surface wind field at sea has been developed. It is supplemented by a semi-automated filter and principle component analysis system to aid in identification of the phenomena responsible each area of intense mesoscale variability.

Task 3:Detailed observational and modeling study focused on determining the forcing, structure, and required conditions for the convectively-driven open ocean squall / lull couplet features frequently seen on SDWS images has been completed.

Task 4:The foundations for the prototype algorithm were completed by Dr. Young this year and will be tested and implemented by Dr. Winstead in FY09.

Task 5:See publication list below.

RESULTS

Task 1: CMOD4 and CMOD5 functions in Matlab have been released for public use along with full documentation, test data, and performance statistics for a geographic region of intense mesoscale variability. The performance of SAR wind speed retrieval in this challenging environment was excellent when compared with direct measurements from three Navy Oceanographic Meteorological Automatic Device (NOMAD) buoys. Both of the commonly used SAR wind speed retrieval models, CMOD4 and CMOD5, performed well although there was some wind speed bias. It is unknown whether this bias was caused by a SAR wind speed retrieval error or a buoy error since buoys are known to underestimate winds as wind speed and, thus, sea state increase. There was little impact on the comparisons from correcting the buoy-derived wind speeds for surface layer stability. The comparisons were also insensitive to the choice of wind direction source: buoy observations or NOGAPS model analyses. It is concluded that useful wind speeds can be derived from SAR backscatter and global model wind directions even in proximity to mountainous coastlines.

Task 2: We have developed a high-pass filtering technique for mapping the mesoscale variability of near-surface wind speed. The filter cutoff scale can be set to either highlight all mesoscale phenomena or only those too small to be resolved by the grid of a particular NWP model. Sample results are shown in Figure 5. In addition, we tested feature extraction and pixel aggregation techniques to aid

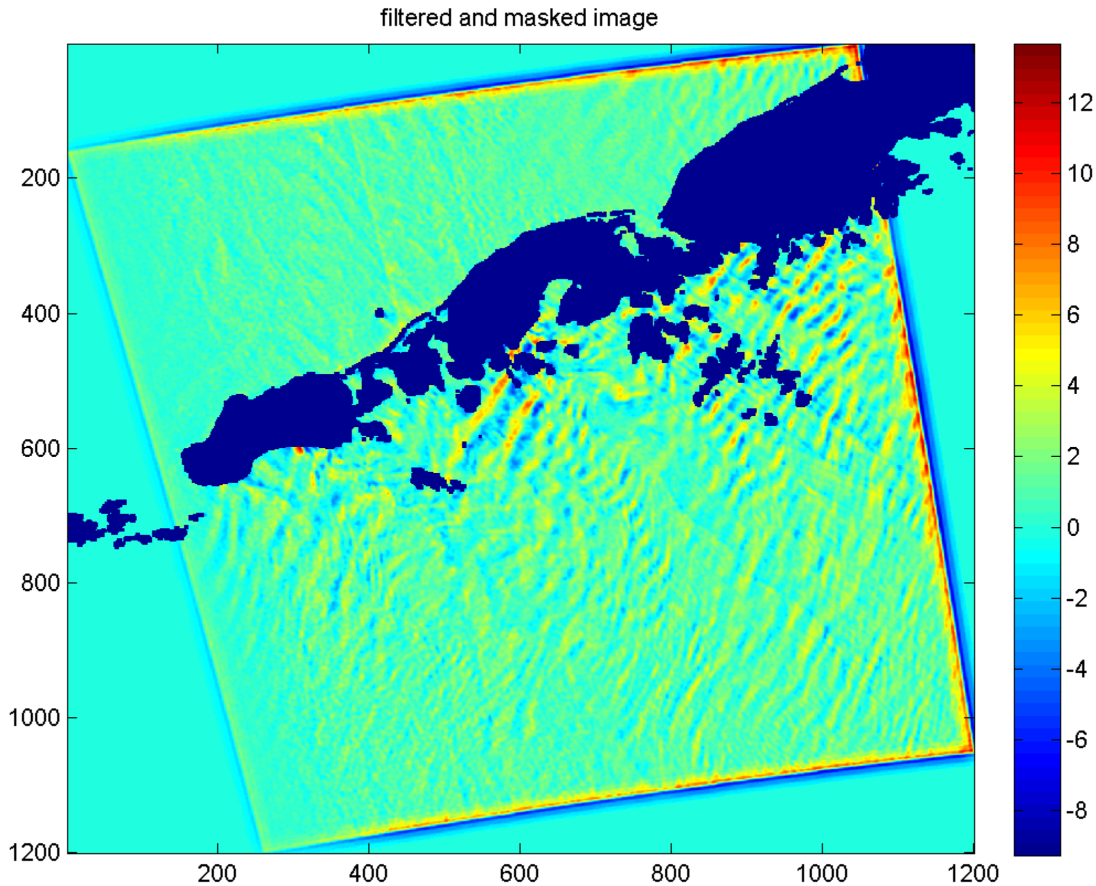

Figure 5. A band-pass filtered Radarsat-1 SDWS image with the synoptic scale background flow and microscale turbulence removed. The resulting image depicts only the mesoscale component of near-surface wind speed variability, in this case weak convective bands north of the Alaska Peninsula and intense orographic gravity waves overlaid on island wakes south of the Alaska Peninsula. The 600 m pixel image is 1200 pixels by 1200 pixels. The image was acquired over the Alaska Peninsula at 0426 UTC on 1 September 2006. The near-surface wind speed varies by 20 m/s in the gravity waves. (Provided courtesy of JHUAPL).

analysts in identifying the particular phenomena responsible for mesoscale variability of SDWS. A sample of twenty eight SDWS images possessing varying degrees of near-surface wind speed variability were selected to serve as case studies. Gaussian high- and low-pass, local entropy, and local standard deviation filters performed well for the feature extraction portion of the research while principle component analysis of the filtered data performed well for the pixel aggregation. A corresponding invited refereed article is in press.

Task 3: We examined open cell convection using two distinct but mutually supporting approaches. The first is a seven-year (1999-2006) climatology of the frequency of open cell convection and the thermodynamic and kinematic environment surrounding its development, based on SDWS images and global reanalysis data. The second approach examines two-dozen case studies from 2006, which employ Moderate Resolution Imaging Spectroradiometer (MODIS) images, SDWS images, and mesoscale numerical prediction model output, to document the morphology of open cell convection. Both approaches are used to reexamine the tropical squall line – open cell convection similarity and corresponding conceptual model proposed in Young et al. (2007). MODIS images showed that open cell convection clouds were typically cumulus congestus along the leading gust front arc, and shallower cumulus completing a ring. Individual open cells produced a squall-lull signature on SDWS images. (The squall is an area of stronger wind with a sharp gradient along its leading gust front.) The climatology showed open cell convection was a cold season phenomenon, having occurred in environments with negative air-sea temperature difference, upward surface heat flux, lower tropospheric structure conducive to latent heat release, and moderate lower tropospheric vertical wind shear vector magnitude. Most case studies occurred during cold air advection southeast of a surface cyclone. MODIS images of the case studies showed that most cumulus congestus clouds were glaciated and most cumulus mediocris and humulus clouds were mixed phase. Lower troposphere static stability and vertical wind shear profiles from the case studies paralleled those of the climatology where comparisons could be made. The cases studies showed that the squall-lull orientation was parallel to the surface layer vertical wind shear vector and the cloud cell orientation was slightly to the right of the surface layer vertical wind shear vector. These findings were then used to revise the conceptual model referenced above. Results are being presented within a conference poster (Sikora et al. 2009) and within a refereed manuscript in preparation.

Task 4: Work not yet addressed.

Task 5: See publication list below

IMPACT/APPLICATIONS

The completed research of Tasks 1 and 2 fulfill ONR objectives by working towards the automated integration of standard meteorological NWP model output and SAR data with the goal of providing high-resolution analyses of near-surface wind speed, direction, and gust intensity in *in situ* data-sparse regions over the ocean, including the littoral zone. Moreover, observational results associated with Task 3 will lead to improved forecasts of the same variables.

TRANSITIONS

None

RELATED PROJECTS

Dr. Sikora is collaborating with Dr. Winstead and National Weather Service Weather Forecast Office Juneau meteorologists on a NOAA-funded project to study the meteorological uses of SAR in the small inlets and mountain gaps that riddle the southeast coast of Alaska. The project goal is to determine the accuracy of SDWS in gap flows under various synoptic scale situations (i.e., develop an error climatology) and to assess the impact of improved wind directions in these critical locations. This NOAA-funded project is closely aligned with Task 4.

Dr. Winstead and the JHU/APL team had applied for NASA funding to standardize and distribute all SDWS data archived to date at APL. Unfortunately, this proposal was declined. However, the APL team continues to seek out sources of funding to accomplish this task. Currently, APL and NOAA are in discussions on a timeline for re-writing ANSWRS and standardizing the output. It is possible that this work will begin in FY09. A standardized output wind product would be relevant for all aspects of this work.

Dr. Young is part of a Penn State and NCAR team addressing the mesoscale modeling of the mesoscale wind variability caused by spatial variations in cloud cover and soil moisture. Many of the implications of this over-land work are equally applicable to the circulations driven by sea surface temperature variations. Dr. Young has focused on the fluid dynamic similarity theories for such buoyantly-driven mesoscale phenomena, including gravity currents, solenoidal circulations, and convection. Large Eddy Simulation has been used to verify the similarity theory for formation of solenoidal circulation and is in use to test those for the existence of local mixed layer similarity within such circulations and for the phase locking of boundary layer convection by solenoidal circulations of similar horizontal scale.

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PUBLICATIONS

a. Previously reported:

Fisher, C. M., G. S. Young, N. S. Winstead, and J. D. Haqq-Misra, 2008: Comparison of synthetic aperture radar-derived wind speeds with buoy wind speeds along the mountainous Alaskan coast. *J. Appl. Meteorol. Clim.* **47** 1365 – 1376. [refereed]

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b. New:

Sikora, T. D., G. S. Young, C. M. Fisher, and M. D. Stepp, 2009: Remote sensing of high-latitude open cell convection. *Sixteenth Conference on Air-Sea Interaction*, AMS, Phoenix, AZ, 11-15 January 2009, poster publication.

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